The Status of VHE Gamma-Ray Astronomy

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I present a summary of the status of the field of very high-energy (VHE) gamma-ray astronomy, as of early 2006. This paper is based on the Rapporteur Talk given at the 29th International Cosmic Ray Conference (ICRC 2005) in Pune, India (August 2005). It covers astrophysical results from observations made by high-energy and very high-energy telescopes operating at photon energies above 1 GeV. The majority of recent observations in this field have been made by ground-based telescopes using the atmospheric Cherenkov or air shower techniques.

In this paper, I try to accomplish two tasks: first, to present a broad overview of the many papers presented at ICRC 2005 in the sessions on gamma-ray astronomy, and second, to provide a status report of the field that highlights the key results that have been reported in the last two years (since ICRC 2003 [1]). Some subjectivity is unavoidable in the selection of results to present in summaries of this type, and there are interesting results that are not discussed here.

A number of results presented at ICRC 2005 were preliminary in nature and have been subsqeuently updated with a journal submission. In addition, there have been a number of significant new results that have been reported since the conference. Wherever possible, I have attempted to reference journal submissions or publications that have occurred since ICRC 2005.

1. Introduction

This paper summarizes the presentations made at ICRC 2005 in the following sessions:

1. OG 2.1: Diffuse X-rays, γ-rays.

2. OG 2.2: Galactic sources (SNRs, pulsars, etc.).

3. OG 2.3: Extragalactic sources (AGN, clusters, etc.).

4. OG 2.4: Gamma-ray bursts.

5. OG 2.7: New experiments and instrumentation.

A total of 207 papers were presented in these sessions; they were approximately divided equally between oral and poster presentations. At ICRC 2005, there were relatively few contributions relating to X-ray astronomy and to γ-ray astronomy below 1 GeV. Thus, to a very large extent, the core subject area covered in these sessions was γ-ray astronomy above 1 GeV (and particularly the observational results from ground-based telescopes operating in the very high energy (VHE) regime above 50 GeV). This paper concentrates on the results presented from currently operating telescopes. Due to space constraints, significantly less emphasis is placed on instrumentation, although there is a brief discussion towards the end of the paper on the major, upcoming future telescopes.

Table 1. Currently operating VHE gamma-ray telescopes. The name of each telescope is given, along with its type (AC=Atmospheric Cherenkov), location, altitude, specifications, and reference at this meeting. The specifications list the currently installed detector area (mirror area for atmospheric Cherenkov and instrumented detector area for air shower). There is no reference at this meeting for the CACTUS telescope.

Experiment	Type	Location	Altitude	Specifications	Ref.
CACTUS	AC-Sampling	Barstow, USA	640 m	144 x 42 m^2	
CANGAROO-III	AC-Imaging	Woomera, Australia	165 m	4 x 78 m^2	[5]
HESS	AC-Imaging	Gamsberg, Namibia	1800 m	4 x 110 m^2	[6]
MAGIC	AC-Imaging	La Palma, Spain	2250 m	1 x 226 m^2	[7]
PACT	AC-Sampling	Pachmarhi, India	1075 m	25 x 4.5 m^2	[8]
SHALON	AC-Imaging	Tien Shan, Kazakhstan	3338 m	1 x 11 m^2	[9]
STACEE	AC-Sampling	Albuquerque, USA	1700 m	64 x 37 m^2	[10]
TACTIC	AC-Imaging	Mt. Abu, India	1400 m	1 x 9.5 m^2	[11]
VERITAS	AC-Imaging	Mt. Hopkins, USA	1275 m	2 x 110 m^2	[12]
Whipple	AC-Imaging	Mt. Hopkins, USA	2250 m	1 x 78 m^2	[13]
ARGO-YBJ	Air Shower	Yangbajing, Tibet	4300 m	4000 m^2	[14]
GRAPES-III	Air Shower	Ooty, India	2200 m	288 x 1 m^2	[15]
Milagro	Air Shower	Los Alamos, USA	2630 m	4800 m^2	[16]
Tibet	Air Shower	Yangbajing, Tibet	4300 m	761 x 0.5 m^2	[17]

2. Experimental Summary

The spectrum of high-energy photons is divided into the X-ray and γ-ray bands, which typically overlap at photon energies of 100-200 keV. The major X-ray satellite instruments operating at the present time are RXTE, ASCA, Chandra, and XMM-Newton. In the γ-ray band between 100 keV and 100 MeV, the operating satellite telescopes are HETE-2, Swift, and INTEGRAL. At this meeting, there was a comprehensive summary of the scientific results so far obtained with the INTEGRAL mission [2]. There is currently no operating space-based telescope with significant sensitivity to high-energy γ-rays above 100 MeV. The last major telescope in this band was EGRET on the Compton Gamma Ray Observatory (CGRO) which operated between 1991 and 2000.

Gamma rays at energies above 100 GeV have been typically divided into the Very High Energy (VHE) and Ultra High Energy (UHE) bands [3, 4]. However, times change, and with so much interest now focused on the GeV and TeV wavebands, it is simplest to define a single VHE band for all energies $E > 50$ GeV. Currently, all telescopes with significant sensitivity in the VHE band are ground-based instruments that use the atmospheric Cherenkov or air shower techniques.

A gamma ray entering the Earth's atmosphere interacts with an air molecule to produce an electron-positron pair. This pair radiates photons via the bremsstrahlung process and an electromagnetic cascade develops, creating an air shower in the atmosphere. Charged particles (mostly electrons) in the air shower radiate Cherenkov light that is beamed to the ground with a cone opening angle of $\sim 1.5°$. *Atmospheric Cherenkov Telescopes* detect VHE γ-rays by capturing the rapid (~ 5 ns) Cherenkov flashes amidst the background of night sky photons.

These telescopes use large optical mirrors to focus the mostly blue Cherenkov radiation onto fast photomultiplier tubes (PMTs). The primary advantages of the atmospheric Cherenkov technique are high sensitivity, excellent angular resolution and energy resolution, and relatively low energy threshold. The disadvantages are moderate duty-cycle ($\sim 10\%$) and small field-of-view (FOV). The Cherenkov telescopes operating today include CACTUS, CANGAROO-III, HESS, MAGIC, PACT, SHALON, STACEE, TACTIC, VERITAS. and Whipple. CACTUS, PACT, and STACEE are examples of wavefront-sampling telescopes that use an array of mirrors to gather the Cherenkov radiation, measuring the arrival time and amplitude of the Cherenkov pulse at many distributed locations on the ground. The other telescopes are examples of the more established imaging Cherenkov technique where the Cherenkov radiation is focused onto an imaging camera at one or more locations on the ground. See Table 1 for a summary of the atmospheric Cherenkov telescopes.

Some fraction of the charged particles and photons in VHE air showers reach the ground level and can be detected by *Air Shower Telescopes*. These telescopes typically consist of charged particle detectors (scintillators or resistive plate counters) spread out on a grid and often covered by a lead layer to convert the photons in the shower, or water Cherenkov detectors in which a large tank of water is viewed by a number of fast PMTs. The primary advantages of the air shower technique are high duty-cycle and very wide FOV. Disadvantages are moderate sensitivity, energy resolution and angular resolution, and relatively high energy threshold. Thus, the two major ground-based techniques for detecting VHE γ-rays are fully complementary – both techniques have proven essential in exploring the VHE sky. The air shower telescopes operating today include ARGO-YBJ, GRAPES-III, Milagro, and Tibet (see Table 1).

3. Scientific Highlights

ICRC 2005 was an exciting and very fruitful conference, with many new results presented. Rather than simply enumerate all the many papers in an encyclopedic fashion, it is valuable to highlight the most noteworthy scientific results that were presented.

The most compelling new results in the area of VHE astrophysics presented this year are the following:

1. The discovery of many new sources in the Galactic plane. HESS reported results from a deep survey of the galactic plane, and from subsequent follow-up observations, that present evidence for a significant number of new sources. Some of these new sources can be well-correlated with known astronomical objects, but other sources cannot be easily identified. An important new source whose γ-ray processes are not understood is the Galactic Center.

2. Detailed studies made of galactic sources. For the first time, a number of sources have been well mapped in terms of their spectra and their spatial extent. The observational work has been carried out by atmospheric Cherenkov telescopes, especially HESS, but there has been, in addition, considerable progress made on the theoretical side.

3. The discovery of four new active galactic nuclei (AGN) by HESS and MAGIC and measurements of AGN properties by a number of atmospheric Cherenkov telescopes. Three of new AGN sources are in the redshift range of 0.15-0.20, making them the most distant extragalactic sources yet detected at very high energies – this could well have implications for our understanding of the extragalactic background light.

4. Other new discoveries and measurements. Significant new results are the discovery of diffuse radiation in the galactic plane and of broad emission in the Cygnus region by Milagro. The galactic plane result represents the first detection of diffuse emission at very high energies. In addition to these results, there

are a number of interesting measurements of properties of known sources and searches for new galactic and extragalactic sources.

In the following sections, we present the results from the first item above - the HESS Galactic plane survey and then discuss the new results divided up by source class.
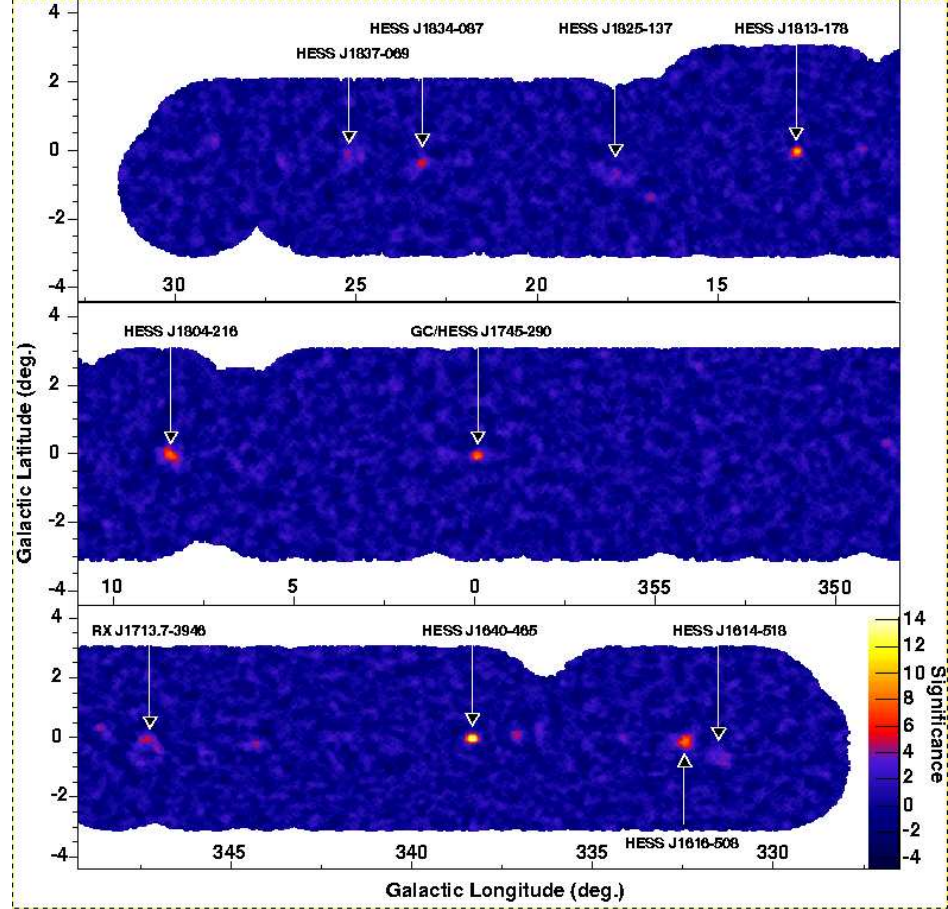
3.1 HESS Galactic Plane Survey

HESS reported results from their survey of the central region of the Galactic plane [18]. The survey was carried out in 2004 with the completed four-telescope array, and it covered a region in Galactic longitude from l = -30° to l = 30°. The coverage in Galactic latitude was approximately b = ±3°. HESS used ∼ 230 hrs to carry out the survey (including additional time for follow-up observations in the Galactic Center, RX J1713-3946, and other regions). The average flux sensitivity of the survey was 3% of the Crab Nebula at energies above 200 GeV. Eleven sources were detected with a post-trials statistical significance greater than six standard deviations ($> 6\sigma$). Of these sources, only two (Galactic Center and RX J1713) had been reported previously at very high energies. In addition, HESS reported seven new sources with a post-trials statistical significance greater than four standard deviations [19]. Figure 1 shows the significance map for the HESS survey.

There are several strong indications that the sources detected by HESS have a galactic, rather than extragalactic, origin. First, the sources are concentrated along the galactic plane with a mean Galactic latitude of -0.17°. Second, the width of the Galactic latitude distribution is consistent with the distribution of young pulsars and supernova remnants in the Galaxy. Finally, all of the sources are extended beyond the size of the HESS point spread function, a result that would rule out, for example, an AGN component. The supernova remnant RX J1713-3946 is the source observed with the largest spatial extent.

We expect VHE γ-rays to be produced as a result of extreme non-thermal particle acceleration. In principle, the observed γ-ray emission can come from non-thermal bremsstrahlung or inverse-Compton scattering processes involving relativistic electrons or from the decays of neutral pions produced from the interactions of protons and nuclei with ambient material. Potential sources in our Galaxy include pulsars and pulsar wind nebulae (PWN), supernova remnants (SNRs), microquasars, and regions associated with massive star formation. It is obviously essential to correlate the VHE sources detected in the Galactic plane with known objects in order to establish the various source classes and to search for new, and unexpected, types of VHE γ-ray emitters. The HESS group has made a systematic study of possible counterparts for the sources detected in their survey – a summary of this study at the time of ICRC 2005 is shown in Table 2. (More complete information can be found in [19]).

As shown in Table 1, four of the sources from the survey are firmly identified with known objects: SNR RX J1713-3946, the Galactic Center (SGR A), SNR G0.9+0.1, and the microquasar LS5039. Of the remaining sources, five have possible associations with supernova remnants or pulsar wind nebulae, one (HESS J1837-069) has a possible association with an unidentified ASCA X-ray source, and two sources (HESS J1614-518 and HESS J1804-216) do not have any well-motivated association.

In addition to using the angular overlap with known objects, the identification of the HESS sources can be further explored using the measured VHE spectra and using the correlation with maps of atomic and molecular constituents. The latter study is important for understanding if the VHE emission is correlated with sites of enhanced interstellar matter density, a possibility that would be expected if, for example, gamma rays result from the collision of accelerated cosmic rays with clouds of interstellar material. The typical spectrum for the sources is hard, with an average spectral index of $\alpha \sim 2.3$, an observation that generally supports the notion of Fermi acceleration. An early, but extremely interesting, comparison of the survey results with maps of CO and

Figure 1. Significance map of the HESS Galactic plane survey carried out in 2004 [18]. The survey covered 60° in Galactic longitude (horizontal axis) and approximately ±3° in Galactic latitude (vertical axis). Eleven sources were detected in the survey with a statistical significance greater than six standard deviations, as labeled in the figure. More complete results on additional data, including more discovered sources, have been recently reported [19].

HI was presented, indicating possible association with molecular clouds along the line of sight in the case of a few sources [29].

4. OG 2.1: Diffuse γ-ray Sources

The majority of the γ-rays detected by EGRET can be ascribed to diffuse radiation from the interactions of cosmic rays with gas and dust in the disk of the Galaxy. This galactic diffuse γ-radiation is generally well modeled at energies below 1 GeV, but above 1 GeV there is a well known discrepancy between the observational data and the model predictions, with the data showing a statistically significant flux excess. There has been a great deal of speculation in the literature as to the origin of the "GeV excess", covering the range from astrophysics (a population of new high-energy sources or harder spectra for the cosmic-ray protons or electrons) to nuclear

Table 2. Possible counterparts to the sources detected in the HESS survey of the Galactic plane. The first column gives the sources listed by the HESS source name. The second column gives the possible counterpart (SNR=supernova remnant, PWN=pulsar wind nebula, and UNID= unidentified source from EGRET, ASCA or INTEGRAL). The Association column gives a subjective determination of the strength or likelihood of the association. The Reference column identifies the corresponding paper submitted to this meeting. All sources were detected with a significance greater than six standard deviations except the source HESS J1826-148, marked by an asterisk.

HESS Source	Possible Counterpart	Association	Ref.
J1713-397	SNR RX J1713.7-3946	Firm	[20, 21]
J1745-290	Galactic Center (SGR A)	Firm	[22]
J1747-281	SNR G0.9+0.1	Firm	[23]
J1826-148*	μ-Quasar LS 5039	Firm	[25, 26]
J1614-518	-	Unknown	[18]
J1616-508	PWN (PSR J1617-5055)	Tentative	[18]
J1640-465	SNR/UNID (G338.3-0.0)	Tentative	[18]
J1804-216	SNR (G8.7-0.1)/PWN (PSR J1803-2137)	V. Tentative	[18]
J1813-178	SNR (GG12.8-0.0)	Tentative	[18]
J1825-137	PWN/UNID (PSR J1826-1334)	Tentative	[27, 28]
J1834-087	SNR (G23.3-0.3)	Tentative	[18]
J1837-069	UNID (AX J1838.0-0665)	Tentative	[18]

physics (modified interaction cross-sections for the cosmic-ray collisions with material in the Galactic plane) to particle physics (dark matter annihilations). At ICRC 2005 there were relatively few submissions on this topic, perhaps because many in the community now realize that the launch of GLAST in two years should substantially improve the observational situation; one paper suggests an important contribution to the excess comes from X-ray binaries [30] and a second outlines the expected emission from supernova remnants [31].

Although there is not yet a generally agreed upon explanation for the EGRET GeV excess, the importance of measurements made by ground-based instruments is widely acknowledged. Such measurements provide the important extrapolation of the EGRET results to very high energies and could, in principle, lead to a map of the diffuse radiation with much higher angular resolution than EGRET. Several VHE telescopes reported results from observations regions of the Galactic plane. Here, we first discuss the results from observations of the plane as a whole, and then we turn our attention to results from observations of specific regions in the plane.

4.1   Galactic Plane – Overall

Milagro, a water Cherenkov air shower array operating at a median energy of $\sim 3.5\,\mathrm{TeV}$, reported on observations made over a three year period of two regions in the Galactic plane: 1) Galactic longitude l = 40° to l = 100° and 2) Galactic longitude l= 140° to l = 200° [32, 33]. Both region encompass Galactic latitudes |b| < 5°. In the first region (inner Galaxy), a detection of a signal with a statistical significance of 4.5 standard deviations is reported, corresponding to an integral flux of $\Phi(E > 3.5\,\mathrm{TeV}) = 6.4 \pm 1.4 \pm 2.1 \times 10^{-11}$

photons $cm^{-2} s^{-1} sr^{-1}$. This result is consistent with an extrapolation from the 1-30 GeV flux measured by EGRET to 3.5 TeV using a differential spectral index of approximately $\alpha \sim 2.6$. The observed flux could be due to both unresolved point sources and true diffuse emission from the Galactic plane. In the second region (outer Galaxy), however, no evidence for a signal is obtained by Milagro and a limit on the integral γ-ray flux is obtained $\Phi(E > 3.5\,\mathrm{TeV}) < 5.0 \times 10^{-11}$ photons $cm^{-2} s^{-1} sr^{-1}$ (99% CL). The limit is not a significant discrepancy with the extrapolated EGRET spectrum as one expects a lower flux in the outer region of the Galaxy.

The Tibet air shower array reported improved limits on the diffuse Galactic γ-ray flux at energies of 3 and 10 TeV [34]. These limits are not in disagreement with the results from Milagro – they lie just above the extrapolation of the EGRET flux using a differential spectral index of 2.6.

4.2 Galactic Plane – Selected Regions

Results from observations of specific regions of the Galactic plane were reported by a number of instruments. Both Milagro and HESS reported noteworthy detections of diffuse emission at TeV γ-ray energies.

As an instrument with a wide-FOV, Milagro is well-suited to making a survey for γ-ray emission over the entire overhead sky. The search for extended sources is an extension of the general survey, and in this search there were two regions that showed strong evidence for VHE γ-rays: the Cygnus region near the Galactic plane and the Crab Nebula region. A more detailed study of the Cygnus region was made using an angular square bin size that varied from $2.1°$ to $5.9°$ [35]. For the largest bin size of $5.9°$, a diffuse source of VHE γ-rays was detected in the Cygnus region with a pre-trials statistical significance of 6.7 standard deviations. The authors estimate the probability for a chance detection of this excess due to a statistical fluctuation to be 1.0×10^{-5} [36]. The excess appears to be spatially correlated with the diffuse γ-ray emission detected by EGRET at GeV energies in this region, and approximately $5°$ away from the unidentified HEGRA source TeV 2032+4130. Figure 2 shows the significance map resulting from the Milagro observations.

The Galactic center is probably the richest region that we can study in terms of potential VHE sources, both point and diffuse sources. CO observations reveal approximately 50 million solar masses of molecular clouds in the central 300 parsecs of the Galaxy. HESS reported on a detailed study of the Galactic center region using 50 hrs of data taken in 2005 [37, 38]. As discussed earlier, they detect two strong points sources in this region (HESS J1745-290 and HESS J1747-281, see Table 1). After subtracting the estimated signal from these two sources, HESS reports evidence for diffuse γ-ray emission along the plane, with a pre-trials statistical significance of 14.6 standard deviations. An important feature of the diffuse excess is that it correlates reasonably well with the molecular material as revealed by sub-millimeter observations. Thus, although there certainly may be additional point sources that are not yet resolved in this study, the data provide strong evidence for the production of γ-rays from interactions of cosmic rays with molecular material.

Limits on diffuse γ-ray emission from selected regions were reported by CANGAROO-III, who observed two regions along the Galactic plane at at energy of 600 GeV [39], and by Whipple, who observed a region in the Cygnus arm of the Galaxy, near to the Milagro excess [41]. Neither limit is inconsistent with the reports discussed above. In the case of the Cygnus region, the Whipple pointing is not coincident with the peak of the Milagro excess and that excess is spread out of a relatively large angular extent. Weak evidence for a diffuse γ-ray signal was presented by TACTIC from an observation in the Crab region [40].
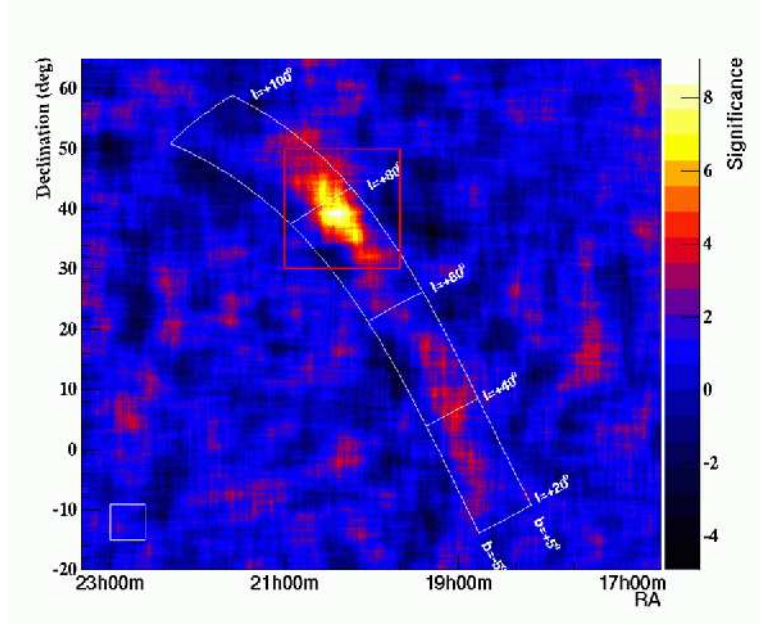
Figure 2. Significance map of Milagro extended source survey in the Cygnus arm region [35]. The color scale shows the excess event significance as a function of right ascension (horizontal axis) and declination (vertical axis). Data are binned in 5.9° bins, so neighboring points are highly correlated. The white boxes indicate ranges of Galactic coordinates. The red box is 20° x 20° region around the bin with the greatest significance.

4.3   Other Diffuse Sources

A variety of other sources of VHE diffuse γ-radiation have been postulated, including starburst galaxies and nearby galaxies that may have a large component of dark matter. Previously, the CANGAROO telescope reported the detection of TeV γ-rays from the starburst galaxy NGC 253 [42]. New observations of NGC 253 have been made by CANGAROO-III, but no results were reported. However, HESS reported results from recent observations that are clearly inconsistent with the original CANGAROO detection. Using data taken in 2003, HESS finds no evidence for γ-ray emission from NGC 253 and sets an upper limit on the integral flux of $\Phi(E > 300\,\mathrm{GeV}) < 1.9 \times 10^{-12}$ photons cm^{-2} s^{-1} (99% CL), assuming a point-like source and an upper limit of $\Phi(E > 300\,\mathrm{GeV}) < 6.3 \times 10^{-12}$ photons cm^{-2} s^{-1} (99% CL), assuming a source size of 0.5° [44, 45]. Thus, the present status of NGC 253 as a VHE γ-ray emitter is very uncertain. A model for diffuse emission from NGC 253 was presented that argued that the VHE γ-ray flux would be hard to detect by atmospheric Cherenkov telescopes, but would possibly be detectable by the future space telescope GLAST [43].

Dark matter in the form of supersymmetric neutralinos could annihilate to produce high-energy gamma rays. Whipple reported a limit on the γ-ray emission from the dwarf galaxies Draco and Ursa Minor and from the galaxies M32 and M33 [46]. The Tibet air shower array reported flux upper limits from observations of M31, M32, and M87, interpreted in the context of dark matter annihilation [47]. The possibility of a dark matter signal in the detected γ-ray flux from the Galactic Center region is discussed in the following section.

Perhaps the most scientifically interesting diffuse radiation is an isotropic radiation that could result from many

unresolved extragalactic point sources or from the injection of very high energy radiation from processes in the early universe. EGRET has measured the isotropic diffuse radiation at energies from 30 MeV to 100 GeV [48]. New measurements of this radiation in the GeV (and possibly TeV) energy bands will likely have to wait until the launch of GLAST. Papers describing models for the extragalactic diffuse emission were presented [49, 50].

5. OG 2.2: Galactic Sources

Understanding the origin of the cosmic rays is one of the most outstanding questions in all of astrophysics. The cosmic-ray spectrum exhibits an unbroken power-law form over an enormous range of energies, from 10^9 eV to 10^{20} eV, and the energy density of the cosmic rays in our Galaxy is ~ 1 eV cm^{-3}, comparable to that in the cosmic microwave background. The fact that the bulk of the cosmic ray are charged, and that the Galaxy has a several μG irregular magnetic field, has hampered our ability to deduce their origin since their directions are scrambled on their way to us. Thus, VHE γ-rays are the most direct probe of extreme, non-thermal astrophysical sources that could be the production sites of the cosmic rays.

Conventional wisdom holds that the bulk of the cosmic rays up to an energy of 10^{14} eV are produced in supernova remnants (SNRs) in our Galaxy. This wisdom comes in part from the issue of energetics – SNRs are perhaps the only Galactic source with sufficient luminosity to power and replenish the cosmic rays – and in part from the fact that we see strong evidence in X-ray data for non-thermal acceleration of particles to TeV energies in SNR shocks. By 2003, evidence for VHE γ-ray emission from a small number of SNRs had been presented, but the significances for these detections were marginal. At this meeting, strong detections of numerous SNRs were reported by several instruments, most notably HESS, and it now appears unambiguous that SNRs are important sources of VHE γ-radiation. A very significant step forward has been taken towards demonstrating that SNRs are in fact the primary sites of high-energy cosmic ray production.

Other potential sources of VHE γ-rays in the Galaxy include pulsars and their associated nebulae (pulsar wind nebulae, PWN), binary star systems (such as microquasars and binary pulsars), and OB stellar associations. All-sky surveys at TeV energies by the Milagro and Tibet air-shower arrays have revealed that there is only one other steady source in the Galaxy with a γ-ray flux comparable to the Crab Nebula (the extended source in the Cygnus region, see Section 4.2), and hence when searching for new Galactic sources, it is critical to achieve a flux sensitivity well below the level of the Crab. The newly commissioned atmospheric Cherenkov telescopes (CANGAROO, HESS, MAGIC, and VERITAS) are all intended to reach this sensitivity.

5.1 Galactic Sources: Old & New

At ICRC 2003, the sky map of Galactic VHE sources contained eight sources that were reported with reasonable confidence [51]. These sources include three PWN (Crab Nebula, PSR 1706-44, and Vela Pulsar), four SNRs (SN 1006, RX J1713-3946, Cas A, and RX J0852-4622) and one unidentified source in the Cygnus region (TeV 2032+413). There was also a hint of something interesting at the Galactic center.

At this meeting, the situation with Galactic sources has changed dramatically as a result of the HESS observations and new detections. In addition to carrying out the Galactic plane survey (Section 3.1), HESS has targeted numerous Galactic sources of interest. HESS reports the detection of 15 new sources that are likely to have Galactic origins. In addition to the 11 new sources listed in Table 2 (RX J1713-3946 had been reported earlier), HESS has detected the composite SNR/PWN MSH 15-52, the binary pulsar PSR B1259-63, an unidentified object HESS J1303-631 (in the same field of view as PSR B1259-63), and a new source in the Vela region HESS J0835-456 (Vela-X). There is also the confirmation of the Galactic center by MAGIC.

Table 3. Galactic VHE sources. A comparison between the VHE Galactic sources established in 2003 and in 2005 is made, showing the dramatic improvement in the source count. The sources are divided by source type; some sources have a tentative association. In addition to the sources listed here, one must include the sources with tentative or unknown associations from the HESS Galactic plane survey (i.e. the eight sources below the line in Table 2). There are thus 20 Galactic sources in the current VHE γ-ray source catalog.

Source Type	2003 Sources	2005 Sources
Pulsar Wind Nebulae (PWN)	Crab Nebula PSR 1706-44 Vela Pulsar	Crab Nebula
		SNR G0.9+0.1 MSH 15-52 HESS J0835-456 (Vela-X)
Supernova Remnants (SNRs)	SN 1006 RX J1713-3946 RX J0852-4622 Cas A	RX J1713-3946 RX J0852-4622 (Vela Jr) Cas A
Galactic Center μ-Quasar Binary Pulsar Unidentified	TeV 2032+413	SGR A LS 5039 PSR B1259-63 TeV 2032+413 HESS J1303-631

HESS also presented the non-detection of three sources: PSR 1706-44, Vela Pulsar, and SN 1006. For PSR 1706-44, the HESS flux upper limits are below the earlier measurements reported by the CANGAROO and Durham telescopes. For SN 1006, the HESS flux upper limits are below the earlier measurements reported by CANGAROO and HEGRA CT1 [1]. Thus, the validity of both objects as probable VHE γ-ray sources is questioned and they are removed from the Galactic source list. For Vela, the HESS source J0835-456 is near the X-ray PWN, but no significant emission is seen at the Vela Pulsar position [23]. Thus, this source is thus named Vela-X to distinguish it from the pulsar [24]. Upper limits on these three sources were also presented by CANGAROO [52, 53].

Thus, in summary, fifteen new Galactic sources were presented at ICRC 2005, but three sources claimed earlier were cast in doubt. The current table of VHE Galactic sources now has 20 objects, as shown in Table 3.

5.2 Pulsar Wind Nebulae and Pulsars

The Crab Nebula was the first source detected at TeV γ-ray energies and is the standard candle for the field. New measurements of the Crab Nebula were reported by a number of instruments at this meeting. HESS reported results from the very strong detection of the Crab Nebula and determined a best-fit centroid location for the VHE emission of (α, δ) = (05h 34m 8s, 22h 1m 11s) with a statistical uncertainty of 5 arc-sec and a

systematic uncertainty of 20 arc-sec [54]. This centroid is consistent with the known positions of the pulsar and the X-ray PWN. The VHE emission is consistent with originating from a point source; HESS placed an upper limit on the extent of the source of < 2 arc-min (99% CL). MAGIC reported results from data taken on the Crab Nebula in 2004 and 2005 [55]; MAGIC measured the energy spectrum from 100 GeV to 6 TeV and is developing methods to push their analysis energy threshold below 100 GeV. A fit to the MAGIC data between 300 and 3000 GeV yields a differential spectral index of $\alpha = 2.58 \pm 0.16$. STACEE reported on measurements of the Crab Nebula between 100 and 1500 GeV using a new technique for γ/hadron separation related to the smoothness of the Cherenkov shower front [56]. Other studies of the Crab were reported by CANGAROO (at large zenith angles) [57] and TACTIC [58].

HESS reported the detection of five new sources that are most likely associated with PWN: SNR G0.9+0.1, MSH 15-52, HESS J0835-456 (Vela-X), HESS J1616-508, and HESS J1825-137, and the non-detection of PSR 1706-44 and the Vela Pulsar (see Tables 2 and 3). SNR G0.9+0.1 was detected in the same field of view as the Galactic Center [23]; this source is a composite SNR, but the VHE emission detected by HESS is consistent with the PWN position and not with the SNR shell. The source is one of the weakest detected (flux $\sim$ 2% Crab) and the energy spectrum measured by HESS is consistent with a single power-law form with differential spectral index of $\alpha = 2.40 \pm 0.11 \pm 0.20$. MSH 15-52 is also a composite SNR, containing a remnant, a 150 ms pulsar, and a pulsar wind nebula. The VHE γ-ray emission detected by HESS is clearly extended along the NE-SW direction [23], in a pattern that is consistent with the X-ray morphology detected by ROSAT. This is the first evidence for an extended PWN source at TeV γ-ray energies. The HESS energy spectrum for MSH 15-52 (flux $\sim$ 15% Crab) is fit by a single power-law shape from 280 GeV all the way up to 40 TeV, with differential spectral index of $\alpha = 2.27 \pm 0.03 \pm 0.20$. The Vela region is rich in potential VHE sources. HESS detected a relatively strong (flux $\sim$ 50% Crab) source, HESS J0835-456 (Vela-X), that is located on the south side of the X-ray PWN [23, 24]. The morphology of Vela-X appears to be extended and the VHE energy spectrum exhibits clear downward curvature above 1 TeV. HESS J1825-137 was discovered during the survey of the Galactic plane and the VHE emission is plausibly consistent with originating from the PWN G18.0-0.7. Like Vela-X, J1825-137 has extended emission that is positionally coincident with one side of the PWN. This may result from the remnant expanding into a inhomogeneous medium. Theoretical modeling to understand the morphology of the PWN and to explain the relatively large size of the PWN was presented by de Jager [27, 28].

Although there is clear evidence that the nebulae associated with pulsar winds produce VHE γ-rays, there have been no detections of pulsed emission at these energies that would come from the pulsar itself. EGRET detected eight pulsars in the GeV range, but the origin of the high-energy pulsed emission in pulsars is still mysterious; the various models (polar cap, slot gap, outer gap, etc.) generally predict cut-offs in the pulsed spectrum in the 1-100 GeV γ-ray range. New upper limits on the flux of VHE emission from the Crab Pulsar were reported by HESS [59], MAGIC [60], PACT [61], and STACEE [56]. The lowest energy points came from MAGIC's limits at the two energies of 90 and 150 GeV, slightly above the energy range explored in an earlier measurement by CELESTE [62]. HESS also reported upper limits on the VHE emission from the Vela Pulsar and PSR 1706-44. The SHALON [9] and PACT [63] telescopes presented results from observations of the Geminga Pulsar, but VHE γ-ray emission from this source is unconfirmed at the present time. The class of rapidly spinning millisecond pulsars are not known to emit γ-rays, but these binary systems are certainly potential targets for VHE telescopes. MAGIC reported results from observations of two millisecond pulsar systems PSR B1957+20 and PSR J0218+4232 [64]; no pulsed or continuous emission was detected from either source and upper limits on the steady VHE emission and the pulsed fraction at energies above 115 GeV were presented.

5.3 Supernova Remnants

As discussed earlier, prior to this year we had evidence of VHE γ-ray emission from four supernova remnants (SNRs): SN 1006, RX J1713-3946, RX J0852-4622, and Cassiopeia A (Cas A). HESS and CANGAROO have confirmed emission from RX J1713-3946 and RX J0852-4622 and have been unable to detect SN 1006 [65, 52]. HESS has also detected three sources in their survey of the Galactic plane that can be plausibly associated with supernova remnants: HESS J1640-465, HESS J1813-178, and HESS H1834-087 (see Table 2). We can now say with confidence that shell-type SNRs are general sources of VHE γ-rays.
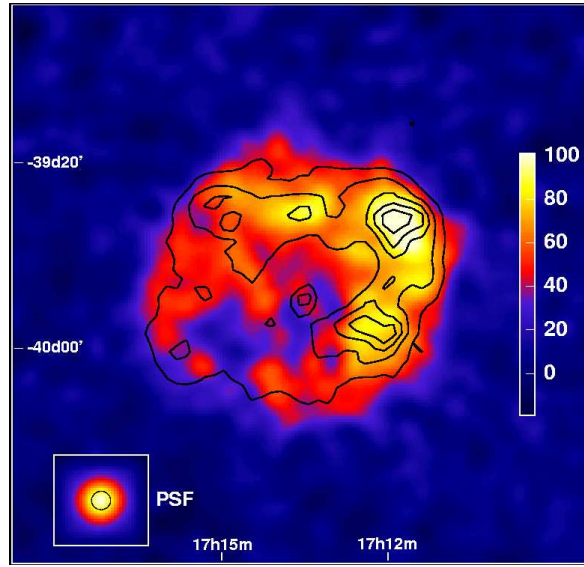
Figure 3. VHE γ-ray excess map of the SNR RX J1713-3946 from HESS [20, 21]. The black contour lines show the surface brightness in 1-3 keV X-rays as measured by ASCA.

RXJ 1713-3946 is a large ($\sim 1°$) SNR that has been well studied by a number of X-ray instruments (ROSAT, ASCA, Chandra, and XMM-Newton). The source was detected earlier by CANGAROO and by HESS using two telescopes in the construction phase. The current measurements by HESS are part of a very strong detection of the source based on 40 hrs of data taken with the full four-telescope array [20]. As shown in Figure 3, HESS well reconstructs the spatial morphology of the γ-ray emission; the SNR shell has been clearly resolved and the VHE emission strongly maps the pattern seen in X-rays. Even more, by dividing the data into three bands of energy ($E < 0.6$ TeV, 0.6 TeV$< E < 1.4$ TeV, and $E > 1.4$ TeV) HESS is able to show that the VHE morphology does not change appreciably with energy. The energy spectrum is well reconstructed from 200 GeV to 30 TeV; the spectral index is hard ($\alpha \sim 2.2$), but the spectrum exhibits curvature and does not well fit a single power-law form. The quality of the HESS data is sufficient to allow spatially-resolved spectral determination - the spectrum measured in 14 different regions of the remnant are not found to vary significantly.

RX J0852-4622 (Vela Jr) is a large ($\sim 2°$) shell-type supernova remnant discovered in the ROSAT all-sky survey and exhibiting non-thermal X-ray emission. The previous CANGAROO detection found evidence for VHE γ-ray emission from one part (NW rim) of the SNR shell. New data from both CANGAROO [52] and HESS [66] confirm that this source is indeed a relatively strong VHE γ-ray emitter. The HESS data show a VHE spatial morphology that is large and extended and is well correlated with the X-ray morphology

as seen by ROSAT at 1-3 keV. HESS measures a relatively hard spectrum with a differential spectral index $\alpha \sim 2.1$. The CANGAROO measurements indicate a somewhat small spatial extent and a somewhat softer energy spectrum. However, the differences between the two experiments are probably not significant at this point. Some uncertainty remains regarding the dominant mechanism behind the VHE γ-ray emission; both electron (inverse-Compton) and proton (π^o) models seem plausible [66], and more detailed modeling is needed to differentiate between these two scenarios. Regardless, RX J0852-4622 is the second shell-type SNR to be detected and well-imaged at VHE γ-ray energies.

In addition to the detections listed already, HESS has carried out an extensive campaign to observe a number of other promising supernova remnants that may be sources of high-energy cosmic rays. Initial results were reported on data taken on five SNRs: W28 (G6.4-0.1), SN 1987A, IC 443 (G189.1+3.0), Monoceros Loop (G205.5+0.5), RCW 86 (G315.4-2.3) [65]. No strong VHE γ-ray emission was found from any of these sources, although there was some evidence of emission from W28. At higher energies, the Tibet air shower array presented upper limits on PeV γ-ray emission from the large Monogem Ring using data taken over a seven year period [67]. The limits are well below the claimed detection by the MAKET-ANI experiment [68]. There were also reported observations of the remnants G40.5-0.5 by the Tibet air shower array [69] and Tycho by the SHALON telescope [9]

The numerous X-ray and VHE γ-ray measurements clearly show that supernova remnants accelerate particles to energies of 50 TeV and possibly higher. The question remains what fraction of the energetic particles are electrons and what fraction are protons. Detailed diffusive shock acceleration models have been developed to explain the broad-band emission from SNRs. A non-linear model for SN 1006 points out the key importance of the density of hydrogen gas that serves as the target material; the HESS non-detection argues for $N_H < 0.1\,\mathrm{cm}^{-3}$ [70]. Another study points out that cosmic-ray ions may also be efficiently accelerated in SNRs and could possibly modify the hydrodynamics of the remnant and require very compressed magnetic fields [71]. The general issue of whether SNRs are the origin of the high-energy cosmic rays was considered in the context of the general non-linear kinetic theory for acceleration [72]. The evidence for strong magnetic field amplification in young SNRs comes from the observation of steep synchrotron spectra and sharp features observed in X-rays. Thus, electrons could in principle be the source of the VHE γ-ray emission, but this scenario would required magnetic fields that are generally not supported by the X-ray data or the models.

5.4 Galactic Center

Understanding the Galactic center region is an important scientific quest. Not only do we wish to understand the center of the galaxy that we live in, but in learning about the Milky Way we could very well derive important important regarding normal, spiral galaxies like our own. The Galactic center has been a promising target for γ-ray telescopes for some time. EGRET detected strong emission from the general region in the MeV/GeV band [73], however the angular resolution of EGRET (and the presence of an ubiquitous glow of diffuse radiation) made a clear interpretation of the nature of this emission difficult.

Previous evidence for VHE γ-ray emission from the Galactic center came from the CANGAROO and Whipple telescopes. At ICRC 2005, both HESS [22] and MAGIC [74, 75] reported detections with substantially improved significance and resolution (spatially and spectrally). HESS reported results from observations made in 2003 and 2004 encompassing over 50 hrs of live time. The detection significance was very high ($> 40\sigma$) and HESS was able to map out the position and extent of the γ-ray emission with excellent precision. With the assumption that the emission came from a point source, HESS localized the emission centroid to within $6 \pm 10 \pm 20$ arc-secs of Sagitarius A* (SGR A*, the putative black hole). However, the HESS data show that the emission has an extension of 1.9 ± 0.2 arc-mins in addition to a point-source like core. A map showing

the positions and error boxes of the various γ-ray observations of the Galactic center is shown in Figure 4. the HESS emission is compatible with an INTEGRAL source, with a supernova remnant (SGR A East), and with the black hole, SGR A*, but is not compatible with a nearby unidentified EGRET source. HESS measured a power-law spectrum that is well fit by a single, unbroken power-law form between $160\,\text{GeV}$ and $10\,\text{TeV}$ with a differential spectral index $\alpha = 2.20 \pm 0.09 \pm 0.15$. The light curve measured by HESS for the five month observation period in 2004 was flat, with no evidence for variability on time scales as short as $10\,\text{min}$. MAGIC reported results from observations made in 2005 encompassing 15 hrs of live time. MAGIC employed the large zenith angle (LZA) technique as the Galactic center culminates at an elevation of $32°$ at La Palma. This lead to an elevated energy threshold of ~ 600 GeV for the observations. The centroid of the MAGIC γ-ray excess is consistent with the position of SGR A* and with a point source hypothesis, given the statistical significance ($\sim 6\sigma$) of the signal. The spectrum measured by MAGIC is hard with differential index $\alpha = 2.3 \pm 0.4$ and in very good agreement with that measured by HESS, as shown in Figure 4.
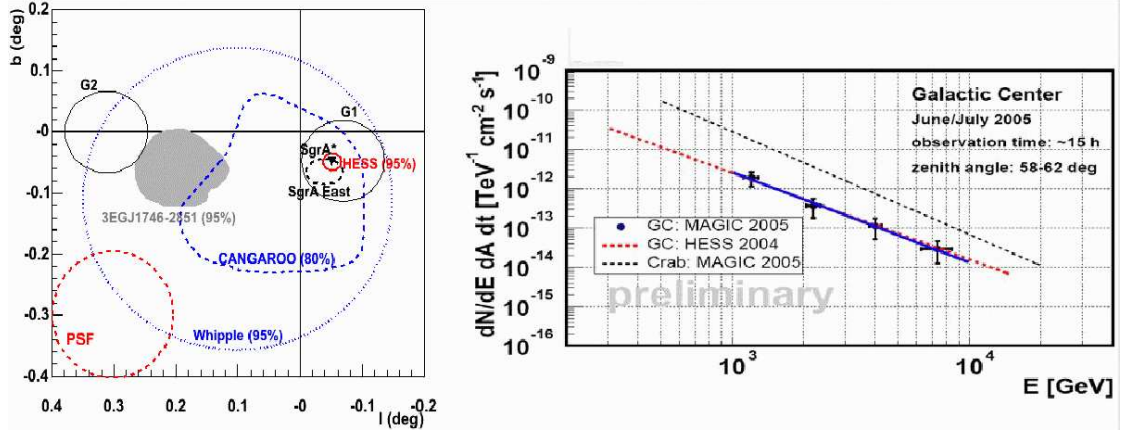
Figure 4. Measurements of the VHE γ-ray source at the Galactic center by HESS [22] and MAGIC [74, 75]. Left: error boxes for the source location as reported by HESS, CANGAROO, and Whipple, as indicated. Solid circles, G1 and G2, indicate INTEGRAL sources and the shaded region indicates an unidentified EGRET source. The locations of Sgr A* (star) and the SNR Sgr A East (dashed black line) are also shown. Right: Differential energy spectrum for the source as measured by MAGIC in 2005. Also shown are the MAGIC spectrum for the Crab Nebula (dark green dot-dash) and an approximation of the Galactic center spectrum measured by HESS (red dot-dash).

Now that the Galactic center is a firmly established VHE source, the question remains as to the nature of this strong, and somewhat unexpected, emission ($\sim 50\%$ of the Crab luminosity at very high energies). Astrophysical possibilities include shock acceleration at the supernova remnant SGR A East (or an obscured SNR or plerion), interactions of stellar winds or VHE cosmic rays with ambient material, non-thermal processes associated with the black hole itself, or something completely different! There is also the tantalizing potential of new physics: dark matter in the form of supersymmetric WIMPs could produce VHE γ-rays through the neutralino annihilation process. Some discussion of the viability of the dark matter hypothesis was presented at ICRC 2005 [76]; no significant constraints on dark matter models can be made at the present time for a variety of reasons. Foremost is the fact that the properties of the VHE emission detected so far are completely compatible with an astrophysical origin, and the region will need to be studied in considerable more detail in order to disentangle the astrophysical contributions to the γ-ray signal. It is perhaps ironic that in the presence of such a strong source of TeV emission, the Galactic center may in fact be a very difficult region in which to

search for dark matter. Other difficulties arise because of the substantial uncertainties in the actual dark matter profile at the core of the Galaxy and in the model parameters for the supersymmetric extension to the Standard Model.

5.5 Other Galactic Sources

As shown in Table 3, three additional types of Galactic sources that have been detected at VHE γ-ray energies are a microquasar, a binary pulsar, and several unidentified objects.

Microquasars generally exhibit strong emission across a broad range of wavelengths, with jets observed in radio and rapid variability in X-rays. The standard picture of a microquasar is a binary system in which a normal star orbits around a compact object. Mass lost from the star falls into an accretion disk where it can be heated and ejected or can fall into the compact object. In some ways, microquasars can be considered active galaxies in miniature, and so there is the hope that by understanding microquasars we can shed light on the mechanisms that power AGN. HESS has observed a number of microquasar targets and reported flux upper limits for four sources, GRS 1915+105 (reported earlier by HEGRA),V4641 SGR, GX 339-4 and Circinus X-1 [77], and detected one source, LS 5039 from data taken as part of the Galactic survey [25, 26]. The nature of the compact object (i.e. neutron star or black hole) in LS 5039 is not clear, and, although the source is relatively dim in X-rays, the fact that it has a massive ($20\,M_\odot$) companion star may have aided in its detection in VHE γ-rays. The HESS data, consisting of ~ 10 hrs of livetime, show a clear detection of a point source whose position is consistent with the known location of LS 5039 and is not consistent with a nearby SNR and pulsar. The HESS source is also consistent with the large error box of the EGRET source 3EG J1824-1514. HESS measured a relatively hard spectrum at very high energies (spectral index $\alpha \sim 2.1$) and although source variability might be anticipated in a microquasar, none has so far been detected from the HESS observations. The establishment of this new source class is an important achievement; more extensive observations of such sources will tell us how prevalent microquasars are at very high energies and whether they provide clues relating to the acceleration processes in active galactic nuclei.

The binary system PSR B1259-63 consists of a 48 ms radio pulsar that orbits a bright and massive ($10\,M_\odot$) Be star. Radio and optical observations indicate that the Be companion has a dense stellar disk, presumably formed from mass outflow. The 3.4 yr orbit of the pulsar is highly eccentric, causing the pulsar to pass within ~ 20 star radii of the companion at periastron. HESS reported on observations taken in early 2004 , before and after periastron, followed by observations made in 2005 [78, 79]. The source was well detected in the first observation period, but not in the second. In the first period, the detected γ-ray flux was consistent with coming from a point source and the spectrum was consistent with a single power-law form (spectral index $\alpha \sim 2.7$), but the flux level was highly variable, on time scales of days, as shown in Figure 5. The HESS results thus reveal a new type of VHE γ-ray source and the first variable galactic source discovered at these energies. A general model, that successfully predicted the detection of VHE γ-rays, postulates that the pulsar produces a relativistic wind of electrons with energies exceeding 10 TeV [80]. These electrons upscatter optical/ultraviolet photons from the Be star via the inverse-Compton effect. The TeV emission is expected to be variable as the pulsar wind approaches, and then retreats, from periastron. Although the inverse-Compton scenario qualitatively describes the VHE γ-ray light curve and the multi-wavelength spectral energy distribution (SED), more measurements are required to fully understand this complex system.

A key goal of any wave band of astronomy is to discover new astrophysical sources and new phenomena not yet seen at other wavelengths. The gamma-ray burst (GRB) is the archetypical example of a source first detected at γ-ray energies that would have been very difficult to discover at lower energies. The detection of the first unidentified VHE γ-ray source, TeV 2032+413, by HEGRA thus marked an important milestone for the field
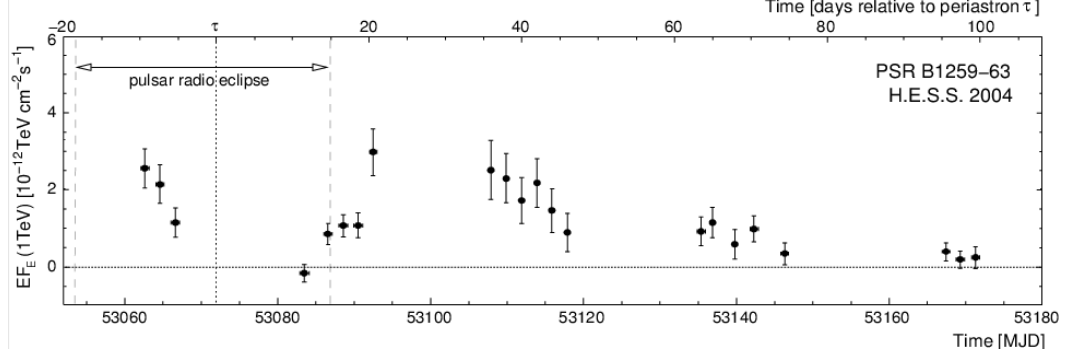
Figure 5. VHE γ-ray light curve of the binary pulsar PSR B1259-63 as measured by HESS in 2004 [78, 79]. The integral γ-ray flux above 1 TeV is plotted as a function of time (in days) relative to periastron. This result marks the first variable Galactic source to be detected at VHE γ-ray energies.

[81]. HESS has reported the detections of four additional sources that are not yet identified, or are poorly identified, with objects at other wavebands: HESS J1614-518, HESS J1804-216, HESS J1837-069, and HESS J1303-631. The first three sources were discovered as part of the Galactic plane survey [18] and are listed in Table 2. The last source, HESS J1303-631, was discovered serendipitously in the same field as the binary pulsar PSR B1259-63 [82]. The source appears to be spatially extended and constant in flux during both the 2004 and 2005 observing periods. No clear counterpart has been identified (e.g. there is no significant X-ray source within the error circle of the HESS detection) [83]. Additional VHE and multi-wavelength observations may clarify the nature of this source, but it is exciting to speculate that this source may represent a new class of "dark" TeV γ-ray emitters. Two other sources, discussed earlier, that do not have a firm or plausible association are the Galactic center and diffuse source in the Cygnus region reported by Milagro [35].

6.   OG 2.3: Extragalactic Sources

Extragalactic sources have been key components of the observing program for VHE γ-ray telescopes for many years. In fact, it is fair to say that until 2004, most of the exciting developments in the field came from observations of extragalactic sources, especially active galactic nuclei (AGN) of the blazar variety.

Blazars (quasars and BL Lacertae, or BL Lac, objects) are important objects that have strong and variable emission at most wavelengths where they are detected. Relativistic jets can be seen, or inferred, in many blazars and the sources often exhibit optical polarization and superluminal motion. The general model for a blazar is one involving a supermassive ($10^6 - 10^9$ M$_\odot$) black hole surrounded by an accretion disk. Matter falling towards the black hole powers the hot accretion disk and perpendicular, highly collimated jets. Blazars are thought to be those AGN whose jets are aligned towards the direction of Earth, and the VHE γ-rays are presumably produced from acceleration processes involving protons and electrons in the jets. The nature of jets (how they form, their composition, their zones of emission, etc.) are a key astrophysical puzzle. In particular, a key question is whether the dominant beam particles are electrons, that produce X-rays via synchrotron radiation and TeV γ-rays via inverse-Compton processes, or protons, that produce TeV γ-rays in cascades resulting from the interactions of protons with ambient radiation fields or material. Previous VHE observations have established that blazars have strong and highly variable γ-ray emission, that their emitted power is dominated by their high-energy emission, that changes in the TeV emission are often directly correlated with changes in the

Table 4. Extragalactic VHE sources. A comparison between the VHE extragalactic sources established in 2003 and in 2005. All blazars are of the BL Lac type. The sources are ordered by their redshift values. There are a total of 11 extragalactic sources in the current VHE γ-ray catalog.

Source Type	2003 Sources	2005 Sources	Redshift
Starburst Galaxy	NGC 253		0.002
Radio Galaxy	M87	M87	0.004
Blazar	Markarian 421	Markarian 421	0.031
	Markarian 501	Markarian 501	0.034
	1ES 2344+514	1ES 2344+514	0.044
	1ES 1959+650	1ES 1959+650	0.047
		PKS 2005-489	0.071
	PKS 2155-304	PKS 2155-304	0.116
	H 1426+428	H 1426+428	0.129
		H 2356-309	0.165
		1ES 1218+304	0.182
		1ES 1101-232	0.186

X-ray emission, and that the sources generally have power-law spectra extending out to 10 TeV (with possible curvature at the higher energies).

Other potential extragalactic VHE γ-ray sources include AGN other than blazars (i.e. radio galaxies such as FR1 and FR2 and radio-quiet spirals such as Seyferts), gamma-ray bursts (GRBs), galaxy clusters, dwarf galaxies, and starburst galaxies. GRBs are discussed in Section 7 and the latter two are discussed in Section 4.3.

An important consideration for extragalactic observations is the potential impact on the detected γ-ray flux from interaction with the extragalactic background light (EBL). The EBL is the total radiation in the infrared(IR)/optical/ultraviolet(UV) bands from normal star formation and radiation from dust, integrated over the luminosity history of the universe. Gamma rays in the 50 - 5000 GeV range will interact with EBL photons via the pair-production process. Since the EBL density is poorly known at the present time, there is promise that spectral measurements of extragalactic sources at a number of redshifts could better determine the density and perhaps constrain cosmological models that impact on the evolution of the EBL. Possible absorption effects in the VHE γ-ray spectra from the sources Markarian 421 (Mrk 421), Markarian 501 (Mrk 501), and H 1426+428 have been previously discussed, but a general interpretation has not yet been established.

The VHE source catalog of extragalactic objects is shown in Table 4. There are currently 11 reasonably well-established sources; ten of these are blazars and one is the radio galaxy M87. Four the blazars, PKS 2005-489, H 2356-309, 1ES 1218+304, and 1ES 1101-232, were discovered in the last year and presented at ICRC 2005. Three of these sources are the most distant objects yet detected at very high energies.

6.1 New Extralactic Sources

HESS reported the discovery three new AGN: PKS 2005-489 [84], H 2356-309 [86], and 1ES 1101-232 [87]. PKS 2055-489 is a relatively nearby BL Lac of the HBL (high frequency peaked) or extreme variety. It was the target of previous observations by the CANGAROO and Durham telescopes, but not previously detected

at VHE γ-ray energies. HESS reported on data taken in 2003 (27 hrs), during the construction phase, and in 2004 (24 hrs), with the full four-telescope array. No significant excess was found in the 2003 data, but the 2004 data showed a statistical significance of 6.7σ, for an overall significance for both data sets of 6.3σ. The source is interesting in being very weak ($\sim$ 2.5% Crab Nebula) and in having a very steep energy spectrum with a differential spectral index $\alpha = 4.0 \pm 0.4$. Given that other, more distant, AGN are detected with harder spectra, it is likely that the steepness of the spectrum observed for PKS 2005-489 results from intrinsic properties of the source, as opposed to absorption by the EBL. No evidence for time variability was found on hourly, daily, and monthly time scales. X-ray data taken in October 2004 with XMM-Newton show a very low state for the source and a very steep X-ray spectrum. Thus, it is possible that this source was detected by HESS in its low VHE state and that flaring and rapid variability may be expected in the future.

H 2356-309 is an extreme BL Lac with an X-ray synchrotron peak near 1.8 keV. Observations by HESS in 2004 totaling $\sim$ 39 hrs of live time yielded a detection with a statistical significance of 9.0σ. The energy spectrum is well fit by a single power-law form with differential spectral index $\alpha = 3.09 \pm 0.16$, as shown in Figure 6. The spectrum is relatively hard at this redshift value which may indicate a lower amount of EBL absorption than had been suggested by the earlier results from observations of Mrk 421, Mrk 501, and H 1426+428. Some evidence was seen for monthly variability in the VHE γ-ray flux.

1ES 1101-232 is also an extreme BL Lac with a flat X-ray spectrum extending up to 100 keV. Observations by HESS in 2004 and 2005 totaling $\sim$ 40 hrs of live time yielded a detection with a statistical significance of 9.0σ, making this the most distant object yet detected at very high energies. No significant variability was detected on a variety of time scales. The energy spectrum for 1ES 1101-232 by a single power-law form with differential spectral index $\alpha = 2.88 \pm 0.17$. As in the case of H 2356-309, this hard spectrum can the interpreted as a constraint on the EBL, i.e. indicating that the EBL density is lower than previously suspected. The energy spectrum of 1ES 1101-232 as measured by HESS is shown in Figure 6.

MAGIC reported the discovery of the BL Lac 1ES 1218+304 from 7 hrs of data taken in 2005 as part of an extensive observation campaign of AGN that targeted eight sources [88] The source was detected with a statistical significance of 7.3σ and with an energy spectrum well fit by a single power law form with differential spectral index $\alpha = 3.3 \pm 0.4$ [89]. No evidence for flux variability has been reported. The energy spectrum of 1ES 1218+304 as measured by MAGIC is shown in Figure 6.

As shown in Figure 6, the spectra for the three most distant AGN detected the VHE γ-ray energies can all be fit by single power-law forms out to energies of 1 TeV and beyond. This observation can be used to constrain the density of the EBL with some assumptions on its shape. The HESS group argue that the AGN spectra constrain the EBL density to be less than half of that expected from a typical model and that the upper limit on the EBL density is approaching a stringent lower limit set by counting resolved galaxies [90]. If the EBL density is significantly lower than expected, we can concluded that the universe is more transparent to VHE γ-rays than was previously thought.

6.2 Extragalactic Source Studies

In addition to reports on the discovery of new AGN, there were many contributions relating to detailed measurements of known extragalactic sources. Here we briefly summarize these contributions and highlight a few of the most interesting results.

The radio galaxy M87, at the center of the Virgo cluster, is a unique object in being the closest, and the only non-blazar, extragalactic source. Originally discovered by HEGRA at VHE γ-ray energies, M87 has been most recently studied by HESS and MAGIC. Some models for M87 suggest that it may be similar to a mis-aligned blazar. It is also considered to be a likely nearby source of ultrahigh energy cosmic rays. The HESS
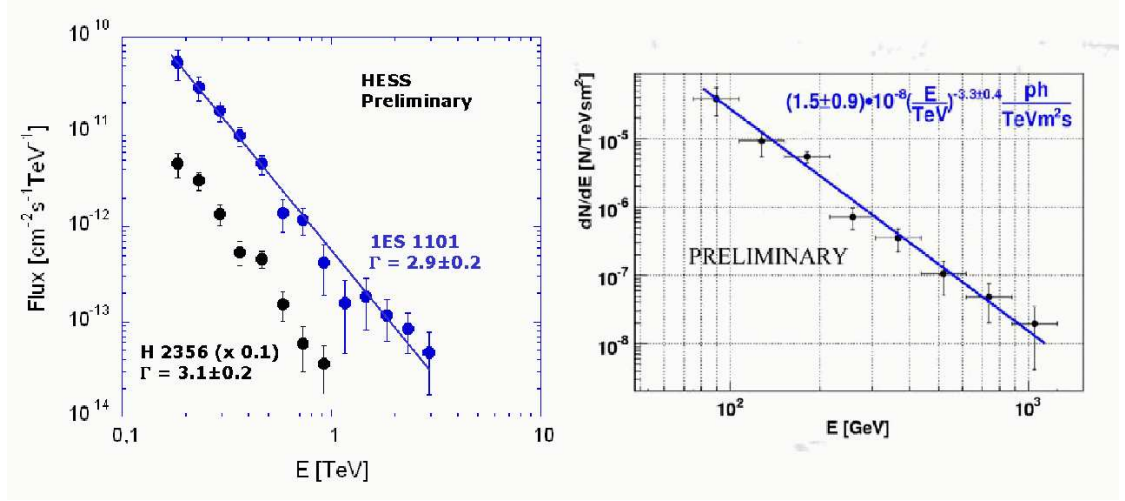
Figure 6. Energy spectra for three new AGN as measured by HESS and MAGIC. Left: HESS spectral measurements of the BL Lac sources H 2356-309 and 1ES 1101-232, with the indicated differential spectral indices [6]. The data for H 2356-309 have been scaled by a factor of 0.1 for clarity. Right: MAGIC measurement of the spectrum for the BL Lac source 1ES 1218+304, with the indicated differential flux determination [89]. Each of these three AGN, the most distant objects detected at VHE γ-ray energies, can be fit by unbroken power laws to γ-ray energies up to, and beyond, 1 TeV.

observations of M87 encompass $\sim$ 31 hrs of live time taken in 2003 and 2004 [91]. The source was detected with a statistical significance of 5.8σ at an energy threshold of 380 GeV, confirming the original HEGRA detection. The HESS γ-ray excess is consistent with coming from a point source that is close to the position reported by HEGRA and is also close to the center of the galaxy. There is evidence for flux variability in that the integral flux measured by HESS is lower than that reported by HEGRA, however more data taken by HESS in 2005 can very likely solidify this possibility. The MAGIC observations of M87 encompass $\sim$ 13 hrs of live time taken in 2005 [92]; no report of a detection was presented at the meeting.

Markarian 421 (Mrk 421) is undoubtedly the best studied AGN at VHE γ-ray energies due, in part, to its brightness and its high degree of variability in both the X-ray and γ-ray bands. The source went into high states in both 2004 and 2005, whereupon it was studied by a number of VHE telescopes. Figure 7 shows some of the results from a five-month monitoring campaign by the Whipple telescope, along with X-ray data from RXTE-PCA [93]. In April 2004, variations of approximately one order of magnitude in size were observed in both the X-ray and VHE γ-ray fluxes. Correlation between the X-ray and VHE flux levels was observed, and the X-ray synchrotron peak shifted upward to above 2 keV during the high state. However, flares on hourly time scales were not resolvable. Similar observations were carried out by HESS [94] and by STACEE [95] during this same period. The HESS observations were made a low zenith angle at energies above 1 TeV, where significant nightly variability was observed. HESS reported an energy spectrum for Mrk 421 that has a clear roll-over at high energies (above $\sim$ 5 TeV) and is best fit by a power-law plus exponential form. The STACEE data were taken from January to April 2004 at a median γ-ray energy of 175 GeV. STACEE uses a new technique to extract the energy spectrum for Mrk 421; the data are well fit by a single power-law form from 100 GeV to 1.5 TeV, with a measured differential spectral index of $\alpha = 1.80 \pm 0.26$. The spectral energy distribution (SED) for the STACEE data, in comparison with the Whipple medium and high states, is shown in Figure 7. The STACEE data show a flattening of the SED at low energies, which might be expected if the

peak of the inverse-Compton component shifts to higher energies during a high flaring state. The TACTIC instrument also made observations of Mrk 421 between January and April 2004; the source was detected with a statistical significance of 6.8σ from $\sim 80\,$hrs of live time [11]. The spectrum in the energy range between 2 and 9 TeV can be fit by a single power-law form for the TACTIC data. Other results from observations of Mrk 421 in 2004 were reported by CANGAROO, operating at low zenith angles [96] and by PACT, where evidence for TeV γ-ray bursts was presented [97]. PACT also reported on multi-wavelength observations of Mrk 421 in 2003, where the source was not detected [98].

Results from recent observations of Mrk 421 were reported by MAGIC for the time period between November 2004 and April 2005 [99] and by the first telescope of VERITAS during the first five months of 2005 [100]. In the MAGIC observations, the source was strongly detected and hourly time variability was clearly observed. Correlation between the X-ray flux from RXTE-ASM and the γ-ray flux recorded by MAGIC was seen, but MAGIC did not see any evidence for spectral hardening or for a flattening in the energy spectrum at energies down to 100 GeV. The VERITAS data showed a significant detection of Mrk 421 and Markarian 501 demonstrating that the telescope design is sound. Some very nice results were presented from coordinated observations of several sources, including Mrk 421, between MAGIC and HESS [101]. For Mrk 421, simultaneous data taken on the night of 18 Dec 2004 show a good agreement between the energy spectrum as measured by MAGIC and HESS, where the spectral data can be fit by a single power-law form across two orders of magnitude in energy.
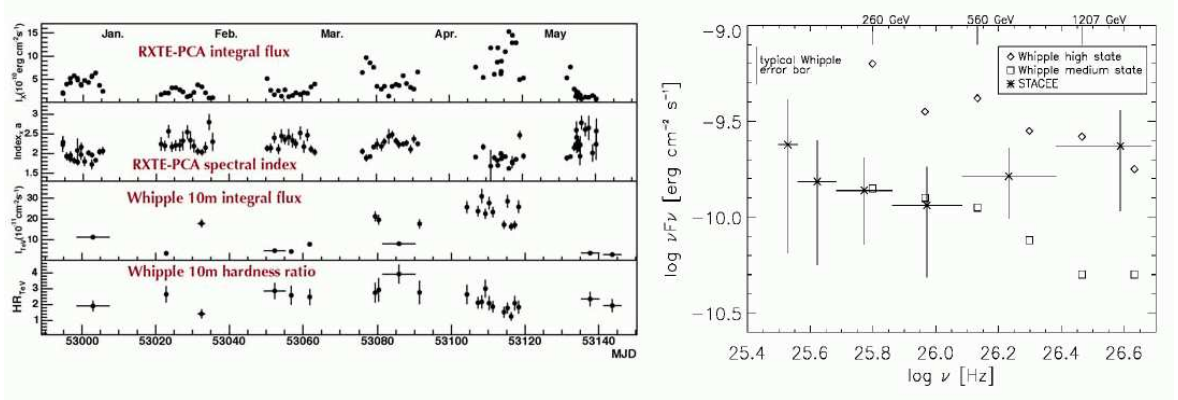
Figure 7. Results from observations in 2004 of the blazar Markarian 421. Left: light curves and spectral information for Mrk 421 for X-ray data from RXTE-PCA and VHE γ-ray data from Whipple for the five month period between January and May, 2005 [93]. Right: spectral energy distribution as measured by STACEE (stars) at energies between 100 and 1500 GeV for data in April 2004 [95]. Also shown are data from Whipple in medium and high flux emission states.

Like Mrk 421, the source Markarian 501 (Mrk 501) is a nearby BL Lac object that has exhibited a high degree of variability. MAGIC reported on data taken in 2005 on Mrk 501 where the source was in a flaring state [7]. On the one night of 1 July 2005, MAGIC detected the source with a statistical significance of 41σ. MAGIC was able to follow the flux variability on 2 min time scales and detected rapid variation on these time scales, as shown in Figure 8. These data may likely represent the shortest time variability ever detected from any VHE γ-ray source and they place strong constraints on the size of the γ-ray emission region. MAGIC also reported on results from observations of the BL Lac 1ES 1959+650 [102]. This source is interesting in that it is difficult to detect in its low state and it has exhibited flaring at VHE γ-ray energies that is unaccompanied by X-ray flaring [103]. The MAGIC data, taken in September and October 2004, show a significant ($\sim 8\sigma$) detection,

but no significant time variability in the γ-ray flux. The MAGIC observations appear to sample the emission from the source in a low or quiescent state.
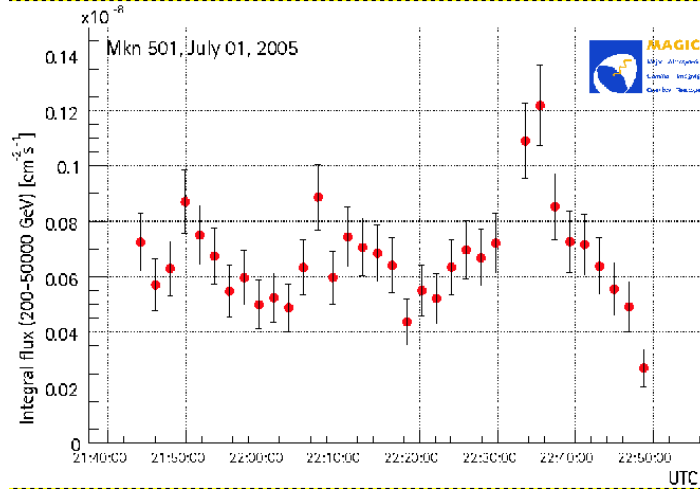
Figure 8. Light curve for the blazar Markarian 501 for 01 July 2005 as detected by MAGIC [7]. The γ-ray flux above 200 GeV is plotted in two minute time bins and rapid variation is observed on that time scale.

PKS 2155-304 was the first extragalactic source detected in the southern hemisphere. Observations of this X-ray selected BL Lac were reported by HESS [104, 105] and CANGAROO [96]. The HESS data, taken in 2003 and 2004, show a variety of interesting features. Although the source was detected overall at a very high significance level ($\sim 100\sigma$), it was also detected at low flux levels in every monthly period it was observed. Multi-wavelength observations in 2003 show no correlation between the X-ray flux as measured by RXTE-PCA and the HESS VHE γ-ray flux; however, the data taken in 2004 do show a positive correlation. The broad-band SED can be fit reasonably by both hadronic and leptonic blazar models, depending on the choice of parameters and on assumptions on the nature of the EBL.

Numerous experiments reported results on searches for other extragalactic sources at VHE γ-ray energies. AGN surveys have been initiated by both HESS [84, 85] and MAGIC [88], with the most important results presented earlier. STACEE reported on extensive observations of two low-frequency peaked BL Lac (LBL) sources, W Comae and 3C 66A [106, 107], the latter as part of a multi-wavelength campaign in 2003-2004. W Comae is a source whose broadband SED is well understood so that a detection at very high energies could potentially distinguish between lepton and proton blazar models. The source 3C 66A is significantly more distant (nominal redshift of $z = 0.44$, but there is uncertainty in this value) than any other AGN detected to date by VHE telescopes. STACEE did not measure a statistically significant γ-ray flux from either source and reported integral upper limits in the 100-200 GeV energy range. In addition to the detection of Mrk 421, PACT reported no evidence of flaring from Mrk 501, H 1426+428, and ON 231 [8]. Similarly, TACTIC reported no detection of the BL Lacs 1ES 2344+514 [108] and H 1426+428 [109]. CANGAROO presented upper limits from observations of the radio galaxy Centaurus-A that might be a mis-aligned BL Lac object [110]. Finally, the Perseus galaxy cluster was observed by Whipple for ~ 14 hrs in 2004-2005 [13]. Galaxy clusters are considered to be promising VHE targets where the γ-rays could originate from the interactions of cosmic ray electrons or protons with material in the cluster. Whipple did not detect a significant γ-ray signal from Perseus and placed flux upper limits from a number of the most luminous radio sources within the cluster.

7.   OG 2.4: Gamma-Ray Bursts

Gamma Ray Bursts (GRBs), discovered serendipitously in the 1960's, are among the most fascinating and enigmatic objects in all of high-energy astrophysics. By demonstrating that GRBs were isotropic in their arrival distribution, BATSE, onboard the Compton Gamma Ray Observatory, gave credence to the idea that GRBs were cosmological in origin. However, the wide non-uniformity of GRBs, in terms of their fluxes, light curves, and spectra, have made their characterization difficult. A key breakthrough was achieved later by the Beppo-SAX satellite which produced accurate GRB positions and carried out X-ray follow-up observations that enabled multi-wavelength observations of the afterglow emission from the class of longer (and softer) GRBs. Redshift measurements of the optical counterparts of GRBs indicate that the longer ones are indeed cosmological with a typical redshift value of $z \sim 1$. Indeed, it is now realized these GRBs are likely the most energetic explosions in the universe, with inferred outputs between 10^{51} to 10^{54} ergs. It is now generally accepted that GRBs are a strongly beamed phenomena, and that when beaming is taken into account their outputs generally cluster near 10^{51}ergs.

Although a great deal is uncertain about the mechanisms behind GRBs, a general paradigm regarding the long bursts has emerged that starts with the explosion of a massive star (collapsar), followed by the rapid formation of a highly relativistic jet. Particle acceleration is carried out by relativistic shocks in the jet, whereby internal shocks produce the prompt emission and then, as the jet collides with the surrounding medium, external shocks produce the afterglow radiation. Many questions regarding GRBs still remain unanswered, including whether they produce significant amounts of very high-energy γ-ray emission. Numerous models predict strong emission at energies up to hundreds of GeV and beyond, however, so far there has only been one detection by EGRET of a photon above 10 GeV. At this meeting, there were just a few papers discussing GRB phenomenology [111] or models [112].

Searches for VHE emission from GRBs or their afterglows have been made by numerous ground-based instruments. To date, there has been no convincing evidence for such emission. The main satellite instruments that currently detect GRBs are HETE-2, INTEGRAL, and Swift. Launched in November 2004, the Swift GRB mission is detecting an unprecedented number of bursts with excellent positional information. Ground-based instruments searching for VHE emission include atmospheric Cherenkov telescopes, air shower arrays, and neutrino telescopes.

Air shower arrays have a high duty cycle and wide FOV that enable them to observe GRBs during their phase of prompt emission. However, the current instruments have substantial collection areas above 1 TeV, reducing the likelihood that they would detect signals from most of the long GRBs that are at cosmological distances. Results were presented by Milagro based on data taken since 2000 [113]. Data from 45 satellite-triggered bursts were analyzed; no evidence for emission from any burst was found and limits on the γ-ray fluence in the energy range between 0.25, and 25 TeV were obtained (assuming no attenuation of the signal due to EBL absorption). Milagro also reported on a generalized search for short duration bursts, independent of a GRB trigger. Data taken over a 2.3 yr period for all positions in the sky were analyzed for bursts with durations ranging from $250\,\mu$s to 40 s; the resulting burst limits were used along with simulations to constrain the VHE spectrum of GRBs [114]. Other results from air shower arrays include first limits from the AGRO-YBJ instrument on a few GRBs from data taken in 2005 [115] and from a general sky survey for steady sources and transients [14] and limits at ultrahigh energies from data taken between 1996-2001 by the Andyrchy EAS array [116]. Reports were made on the feasibility of water Cherenkov tanks for GRB detection as part of the Auger Project [117] and at a high altitude site in Mexico [118].

Atmospheric Cherenkov telescopes have relatively low energy thresholds and high sensitivity, but small fields of view. They are thus well suited for follow-up observations of the afterglows of triggered GRBs. The MAGIC telescope has been designed to provide a very rapid response to GRB alerts. MAGIC reported on observations

of a number of recent GRBs, including one burst (GRB050713A) in which MAGIC started data-taking only 40 s after the burst event [119, 120]. No evidence for VHE γ-ray emission was reported, but this event indicates the significant potential of this new generation of Cherenkov telescopes. The STACEE solar array telescope reported on observations of 14 GRBs made over a several year period, including two Swift-triggered bursts (GRB050402 and GRB050607) in which data-taking started less than four minutes after the GRB trigger [121]. Integral flux limits on GRB050607 were obtained for γ-ray energies above 100 GeV.

8.   OG 2.7: New Experiments and Instrumentation

There were many contributions to ICRC 2005 in the area of future experiments and instrumentation. However, as discussed in the Introduction, this paper will only briefly summarize these contributions because: 1) I am concentrating here on the present scientific status of the field, and 2) there have been numerous meetings discussing instrumentation and plans for future telescopes (e.g. see [122]).

New experiments are under construction, or in the planning stages, in three areas: satellite-borne instruments, ground-based atmospheric Cherenkov telescopes, and ground-based air shower arrays.

8.1   New Satellite Instruments

ASTROSAT is a UV/X-ray mission that is currently under development by a number of institutions in India [123]. Scheduled to launch in 2007, the mission comprises five instruments, spanning the UV, soft X-ray, and hard X-ray bands. The UV Imaging Telescope (UVIT) has waveband coverage between 130-320 nm and an angular resolution of 1.8 arc-sec. The Soft X-ray Telescope (SXT) images X-rays between 0.3-8.0 keV over field of view of $0.35°$. The Large Area X-ray Proportional Counter (LAXPC) is a non-imaging device covering a wide range of energies from 3-100 keV with a geometrical area of 10800 cm^2. The LAXPC will carry out variability and timing studies of X-ray sources with modest energy resolution. The CdZnTe Imager covers X-ray energies between 10-100 keV over a wide field of view, designed to carry out medium resolution studies in the hard X-ray band. The scanning sky monitor (SSM) is a position-sensitive proportional counter to provide X-ray imaging between 2-10 keV over a very wide field of view. The science goals of ASTROSAT are varied, ranging from timing and spectral studies of AGN, SNRs, pulsars, binaries, and galaxy clusters to detection of new X-ray transients.

GLAST is a future, major high-energy γ-ray mission that is being developed by an international consortium and currently scheduled for launch in Fall 2007. The mission consists of two instruments, the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). The LAT comprises a large-area silicon strip tracker, a segmented CsI calorimeter, and an anti-coincidence shield [124]. The LAT will have greatly superior performance relative to EGRET (i.e. an order of magnitude improvement in sensitivity). Of particular importance for VHE astronomy, the LAT will have a relatively constant effective area up to energies of 300 GeV, implying that many sources detected by GLAST will have measured spectra that overlap with ground-based instruments. The GBM is a gamma-ray burst detector that utilizes NaI and BGO crystals to detect and localize bursts in a similar manner to BATSE on the CGRO. The GBM performance will be similar to BATSE but will cover a wider energy range with a smaller collection area. The construction of both the LAT and GBM instruments are largely complete at the present time and full integration of the payload is starting. The major science goals of GLAST are to discover new sources of high-energy γ-rays (e.g. AGN, pulsars, SNRs, GRBs, and new objects), to more accurately measure spectra and positions of sources to understand the mechanisms of high-energy particle acceleration, and to probe dark matter and the early universe via observations of possible neutralino signatures and of distant AGN and GRBs.

In addition to GLAST, the AGILE mission aims to study gamma-ray and X-ray sources in the 30 MeV - 30 GeV and 10-40 keV energy ranges, respectively. AGILE is being developed by a group of Italian institutions for a launch in the 2006-2007 time frame. There was no contribution at ICRC 2005, but details on the mission can be found at their website [125]. There was also a contribution on CASTER, a coded-aperture imaging X-ray telescope in the 10-600 keV band that could be considered for NASA's Black Hole Finder Probe [126].

8.2   New Atmospheric Cherenkov Telescopes

The VERITAS array will consist of four 12 m diameter imaging atmospheric Cherenkov telescopes, to be deployed at a mountain site in southern Arizona, USA [12]. Each telescope images the Cherenkov light onto a 499-PMT array; the PMTs are read out by a 500 MS/s Flash-ADC (FADC) system. As shown in Figure 9, two telescopes have been constructed and deployed at the Base Camp of the Whipple Observatory on Mt. Hopkins, Arizona. The performance of the telescopes (mechanical, optical, electronic) all meet or exceed the design specifications, and the first telescope has been used during 2005 to make astrophysical detections [100]. Figure 9 shows Cherenov events that have been reconstructed by two telescopes. VERITAS is currently scheduled for full operation in late 2006. When operational, VERITAS will be an important complement to MAGIC in the northern hemisphere and to HESS and CANGAROO in the southern.

HAGAR is an atmospheric Cherenkov telescope array currently under development for deployment at the high-altitude Hanle, India site at 4200 m elevation [127]. HAGAR will use the wavefront-sampling technique, employing seven telescopes on a 50 m hexagonal grid. Each telescope will consist of seven para-axially mounted 0.9 m diameter mirrors with a single PMT at the focus of each mirror. Simulations indicate that HAGAR will have a low energy threshold (below 100 GeV) and moderate source sensitivity. The first telescope has been constructed and deployed at Hanle where tests are currently underway, with plans for a full deployment by early 2007.

The MACE instrument is being designed as two very large (21 m diameter) imaging Cherenkov telescopes for future deployment at Hanle [128]. The telescopes will be made up of 356 panels of mirrors, with each panel consisting of either four or nine spherical mirror facets made from diamond-machined aluminum alloy. The MACE cameras will comprise 832 pixels, covering a field of view of $4°$ x $4°$. With its large size and high-altitude site, MACE should have a trigger energy threshold well below 50 GeV. Designs for MACE are currently in the advanced stages with a 4-5 yr construction period envisioned.

The first phase of HESS, consisting of four 12 m imaging atmospheric Cherenkov telescopes was comissioned in late 2003. Planning is underway to construct HESS Phase II [129]; the major component of the upgrade will be a very large 28 m diamter telescope that will be deployed at the center of the HESS-I array in Namibia. The new telescope will significantly improve the energy threshold of HESS and increase its sensitivity. Various options for the reflector are being considered; initial plans call for a rectangular dish (32 m x 24 m) with 850 mirror facets and a parabolic shape. The very large camera will consist of 2048 pixels with a front-end readout that will be redesigned from HESS-I to accomodate the higher trigger rates (~ 3 kHZ). Construction on HESS-II has started with a planned completion time of approximately three years.

MAGIC is also in the process of an upgrade to the original instrument. The major component of MAGIC Phase II will be a second 17 m diameter reflector [130]. Other improvements will be the replacement of the replacement of the standard camera with hybrid photodetectors (HPDs) that have a quantum efficiency near 50% and new FADCs with a sample rate of 2.5 GS/s. These various improvements should lower the energy threshold of MAGIC and improve its sensitivity, especially at energies below 100 GeV. Construction of the second telescope is now well underway with a planned completion date of sometime in 2007.

8.3   Air Shower Arrays

As shown in Table 1, the ARGO-YBJ experiment is an air shower array deployed at the high altitude site of Yangbajing, Tibet. The experiment will eventually consist of a large carpet of resistive plate chambers (RPCs) covering a total area of $6400\,\mathrm{m}^2$ [115]. The RPCs are divided into 18480 pads of size 0.56 cm x 0.62 cm that provide the space-time pattern for measuring the wavefront of the air shower. The experiment is still under construction, but a large portion ($> 50\,\%$) is already installed and operational. ARGO-YBJ has presented early physics results on a variety of topics at this meeting, including a sky-survey and a GRB search. Plans call for the full experiment to be operational in 2006.

A future air shower array using the water Cherenkov technique was also discussed [131]. The HAWC experiment would consist of a 300 m x 300 m pond of water that would be instrumented by a large number of PMTs. A key attribute of HAWC would be its high altitude location ($> 4000\,\mathrm{m}$ elevation) to permit a substantial lowering of the energy threshold relative to Milagro. Detector and sensitivity studies are underway to characterize HAWC. The design of an earlier version of the experiment, called mini-HAWC, that could utilize the existing 900 PMTs from Milagro, is also being actively pursued.
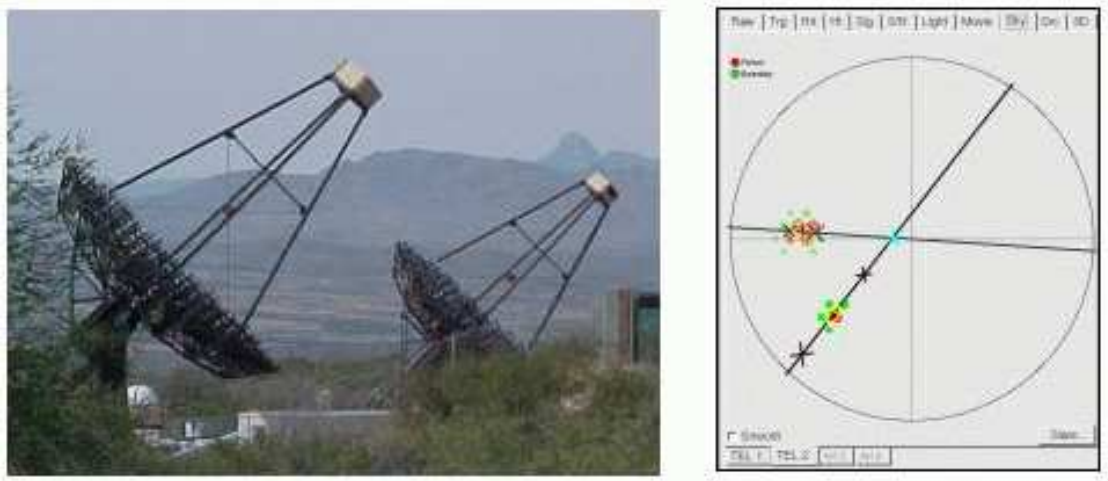
Figure 9. The VERITAS atmospheric Cherenkov telescope array. Left: the first two telescopes VERITAS, operating at the Base Camp of Mt. Hopkins, Arizona, USA [12]. VERITAS will consist of four 12 m diameter telescopes, each equipped with a 499 pixel camera. Right: A stereo Cherenkov event taken with the first two telescopes.

9. Conclusions

The last two years have been exciting times for very high energy (VHE) γ-ray astronomy. Some of the most significant developments are the following:

1. A new generation of atmospheric Cherenkov telescopes has yielded outstanding results, including the discovery of many more sources of VHE radiation.

2. The spatial and spectral properties of VHE sources are being measured with a precision that is unique in gamma-ray astronomy and that, in many ways, exceeds what was done with the Compton Gamma-Ray Observatory, a Great Observatory of NASA.

3. We have learned that the Galactic plane is rich in the number and type of VHE sources, with supernova remnants and pulsar wind nebulae now firmly established as important VHE emitters. Other new sources include a binary pulsar, a microquasar, and the mysterious Galactic center.

4. We have identified a number of new sources that do not have obvious counterparts to objects at other wavelengths. One of these is a broad source in the Cygnus region of the Galactic plane. We are starting the investigation of a new class (or classes) of astrophysical objects that are bright at TeV energies, but dim at other wavebands.

5. The discovery of four new blazars increases the extragalactic source count and pushes our discovery space out to greater redshift values. The fact that the most distant VHE sources have unbroken power-law spectra to the highest energies detected may signal that the universe is more transparent to VHE photons than previously suspected.

6. New experiments on the ground and in space should continue the rapid and exciting development of VHE astrophysics.

10.   Acknowledgments

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